Theory and Methodology of Ecosystem Engineering

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Abstract Ecosystems engineering is specially designed for study and management of ecosystems. Its theory and methodology are mainly derived from systems ecology and systems engineering. An ecosystem is a biologically functional entity consisting of organisms, environmental factors and their interactional mechanisms which are naturally or artificially arranged with their appropriate functions in the system and also subordinated to the dynamics of the whole ecosystem. If an ecosystem is broken or disintegrated into independent or isolated parts, its structural and functional entity will be greatly modified or even completely destroyed. Yet without participation of organisms including human beings, a system is not an ecosystem. Within an ecosystem, all life, production and social activities are directly or indirectly related to the energy flow and material exchange. In fact, energy is a driving force for material exchange and material is the carrier of energy flow. Therefore, an ecosystem can be logically recognized as an energy system. Its components, structure, function, production, quality and benefits can be expressed, calculated and modelled in terms of energy. Ecoboundary theory is also used in the discussion of pathways of energy flow. As being applied to agroforestry management, environmental conservation and community social service which are all complicated ecosystems, ecosystem engineering requires a series of programming measures such as investigation, decision-making, planning, simulating, design, establishment, management, evaluation and renovation so that an appropriate ecosystem with stable structure, effective function and high productivity can be established for its expected economic, ecological and social benefits.

Key words: Systems ecology; Systems engineering; Ecosystem; Ecosystem engineering; Ecological engineering; Ecoboundary.

Introduction

As a branch of system sciences, ecosystems engineering is developed from the practice of ecological engineering for study and management of ecosystems. Its theory and methodology are mainly derived from systems engineering and systems ecology. In this paper an attempt is made to establish mathematical models of energy flow for evaluation and application of ecosystems engineering.

Theoretical Bases

The theory of system sciences is systematology which visualizes that things in the material world are directly and indirectly associated, acted, influenced and conditioned each other and together with their functional processes form a whole systematic entity (Foresters 1968, Sage 1979, Wang 1982, Odum 1982, Qian 983). In dealing with the problems of systems, systems engineering is not only connected with technical measures and their practices known as concrete or "hardware" engineering but also emphasizes the programmatic procedures of organization and management including analysis, desicision-making, planning, modelling, evaluation, coordination, etc. which are collectively called the conceptional or "software" engineering (Hsiung, 1991). Under the guidance of systematology, systems engineering is appropriately implemented for the optimization and effectiveness of diffent systems in view of their specification(Chestnut 1986, Fan and Yu 1990, Goodwin and Payne 1977, Chen, 1988).

As a type of systems, ecosystems are generally organized with land, water, mineral cycles, living organisms and their programmatic behaviour mechanisms (Odum, 1982). Thus ecosystems not only inhere the common characteristics of general systems such as collectiveness, wholeness, sequence and dynamics but also possess some features of their own. Of them the most important is the biological components including plants, animals, micro-organisms and human beings as well. All the living organisms, inorganic environmental materials and their appropriately interaction processes are naturally or artificially formed into biologically functional entities known as ecosystems (Odum 1982, 1989; Hsiung 1985, 1991, 1995; Jorgensen 1992). Apparently, without the participation of organisms a system is not an

ecosystem. Hierarchical structure is another noticeable feature of an ecosystem in which all living things and non-organics are normally arranged acoording to their functional characteristics in the structural sequence and numerical proportion and at the same time subordinated to the functional wholeness of the system (Odum 1982,1989, Hsiung 1991, Mitsch and Jorgensen 1989, Jorgensen 1992).

In a complete ecosystem, life activity of organisms including human beings serves as motive power in material exchange, energy flow and information transmission among organisms-organisms, organisms-enviornments and ecosystem-social system that form a network of material energy flow. Therefore, an ecosystem is more than the sum of its components as they interact on each other (Odum 1982, Mitsch and Jorgensen 1989). In fact, all materials within an ecosystem are carriers of energy and energy acts as conditions and driving force for material exchange. Both work simultaneously at a time. Thus an ecosystem can be logically recognized as a system of energy flow -- energy transformation, feedback interaction and recycling which can be expressed, calculated and modelled in terms of energy flows (Huang, 1993, Hsiung and Huang 1994). In the functional study of ecosystems, an ecoboundary theory was advanced to discuss the pathways of energy flow that has interested many ecologists. There commonly exist boundary areas or interfaces between organisms and their surroundings through which material exchange, energy flow and information transmission take place. If the amount of energy entered into or released from the organisms through ecoboundary layers is measured and calculated in terms of caloric or joule, the vigour of organism and favorableness of surrounding environments can be detected or determined. Accordingly the functional benefits or advantages of the ecosystem can be analysized or predicted. This theory can be applied to the study of agricultural ecosystem (Hsiung and Wang 1986, 1992, Hsiung and Huang 1994).

The main energy source of an ecosystem comes directly or indirectly from the solar radiation. As primary producers, green plants through photosynthesis and related physiological processes absorb external inorganic materials from their surroundings, transmute them into the internal organic matter to build up their bodies and also through dissimilation change a part of their internal matter into external inorganic materials which are released again to the surroundings. Such life activities of green plants create favorable environment and nutritional resources for non-green organisms. Without any human interruption a natural ecosystem is only operated by life activities of its innate organisms. The pathways of its energy flow are relatively simple and regular and the time-space architecture and numerical proportion of its biological components are naturally developed with high dynamics of self - sufficience and self - restoration. On the contrary, however, as humans are involved, the situation is greatly different. Humans are components of an ecosystem, yet they are also dynamic dominators to the ecosystem performance. Human interruptions could cause a series of chaos so that the pathways or networks of energy flow become irregularly more complicated and disordered (Hsiung and Zou, 1985; Hsiung, 1991). With rapid grawth of human population, industrial development and economic expansion in recent years, many ecosystems and environments become so destructively deteriorated or degraded as to be severe social problems of mankind. Indeed anyone who snatches much from an ecosystem far beyond its tolerance will inevitably pay a high price. Many painful lessons have been learned from such human misdeeds as mono-cultural agriculture, large scale forest clear-cutting, overgrazing of grassland, excessive reclamation of wilds and marshes, etc.. All these make an urgent appeal for research and practice of ecosystems engineering.

On the basis of ecological engineering, ecosystems engineering is developed with emphases on the systematic entity in dealing with planning, design, establishment and management which involve much diversity in engineering processes. Its task and purpose are to maintain the wholeness, sequence, dynamics and self-organization of an ecosystem, and also to coordinate and improve the relationship of components within the ecosystem such as time-space sequence, numerical proportion, interaction with environmental conditions and social economy. Thus, structural function of an ecosystem can be brought into full play to achieve expected economic, ecological and social benefits (Hsiung 1991, Hsiung et al. 1995).

Methodological Approaches

For successful establishment and management of an ecosystem which may be a county, a town or a rural area of variable size, serial of programmatic prerequisites should be made:

1. Thorough investigation of its natural conditions, socio-economic background and educational level of the people;
2. Full understanding of its biological and inorganic components, structure and functional characteristics;
3. Analysis and discussion of requirements of the proposed goal;
4. Final decision-making according to the proposed

goal;

5. Qualitative and quantitative mathematical model for further analysis, comparison, forecast and evaluation of the system;

6. Design of an ecosystem according to the optimized model;

7. Establishment of an ecosystem based on the optimized design;

8. Coordination of socio-economic activities related.

As a result, an ecosystem with ideal components, stable structure, effective function and comprehensive benefits can be expected. Such a whole procedure of programmatic measures is called the methodology of ecosystems engineering (Hsiung 1991).

As mentioned above an ecosystem is a biologically functional system which is directly or indirectly related to the life activities of the biological components. Thus methodology of ecosystems engineering focuses its emphasis on the energy flow of the ecosystem (Odum 1982, Hsiung 1991, Zhu 1991, Jorgensen 1992).

An Energy Model advanced by Huang (1993) for describing the dynamic behavior of a life energy system can be used to explain the energy activity and interrelationship of compopnents in an ecosystem, if human interference is considered as a restrictive condition which serves as an undetermined function to be put into equation system of the energy model. The process is "energynization". In an ecosystem with n independent components (or subsystems), the original mathematical form of energy model can be expressed as follows

$$\frac{du_i}{dt} = -A_i u_i^2 + B_i u_i + \sum_{i \neq j}^{n} (C_{ij} - D_{ij} u_i) u_j - \varphi_i = f_i(N_i', \lambda_i') \qquad (1)$$

where the state variable is the energy of component i, the variable energy is directly related to variation of biomass (Odum 1982, 1989, Y. G. Zu 1991), the energy variance rate is governed by the factors in the right side of formula (1) and the formula can be considered as the sum of three parts: the first is $(-A_i u_i^2 + B_i u_i)$ which implies the energy flux acquired from outside of the ecosystem; the second is $\sum_{i \neq j}^{n} (C_{ij} - D_{ij} u_i) u_j$, which implies the energy flux exchanged with other components within the ecosystem; the third is the consumption rate of component i. $A_i, B_i, C_{ij}, D_{ij}, \varphi_i$ are eigen parameters of formula (1), n is the total sum of components in the system. The formula (1) is illustrated in Fig. 1.

Supposing $E(t)$ is a conversion function, which implies to the energy flow of component i from the interference of human economic activity, it means the economic investment in a unit time when $E_i(t) > 0$ and economic benefit when $E_i(t) < 0$. Put $E_i(t)$ into formula (1), we have

$$\frac{du_i}{dt} = f_i(N_i', \lambda_i') + E_i(t) \qquad (2)$$

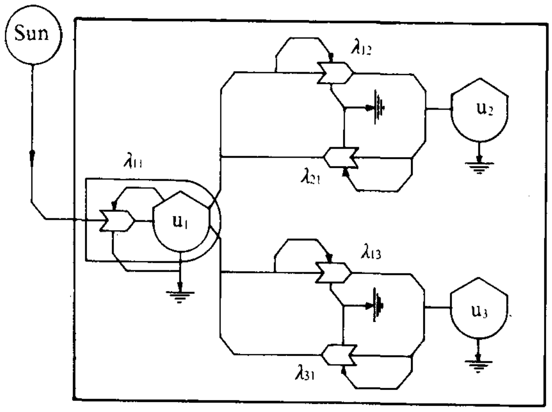

Fig. 1. Sketch map of energy equation

Generally speaking, function $E_i(t)$ consists of $E_{i1}(t)$ and $E_{i2}(t)$, the former is investment and the latter is gain, both may exist at the same time, but in some cases, they can't, just as in the agricultural activities, the investment put into the cultivation of crops is $E_{i1}(t)$, the reaped crop can be considered as $E_{i2}(t)$. Sometimes or in some kind of production process, such as animal husbandry, forestry, or fishery, $E_{i1}(t)$ and $E_{i2}(t)$ may coexist during the same period of time.

In the energy model of an ecosystems engineering, the second part $\sum_{i \neq j}^{n} (C_{ij} - D_{ij} u_i) u_j$ (abbreviated as I_{i2}) plays a role of connecting the other components with energy exchange. When $I_{i2} > 0$, it means the input energy from the other components is greater than the output to them and promotes the growth of component i; otherwise $I_{i2} < 0$, the growth of component i is inhibited. With the transportation function of I_{i2}, some extra energy may diffuse to other components and become useful energy. This may improve the energy --- using efficiency of the ecosystem. For example, in an agricultural ecosystem the dung of animals can be used to fertilize crops or feed fishes, which may save the costs of the fertilizer, feeds and also dung treatment. Using 1, 2, 3 to stand for animal husbandry, fishery and agriculture in an ecosystem respectively, the mathematical expression is to transform I_{11} (waste) into I_{12} ($I_{12} < 0$ and $I_{22} > 0$, $I_{32} > 0$) may reduce $E_1(t)$ the cost of waste disposal, $E_2(t)$, the expense of feeds

of fishery and $E_3(t)$, the agriculture fertilizer. This process is illustrated in Fig.2.(a).(b).

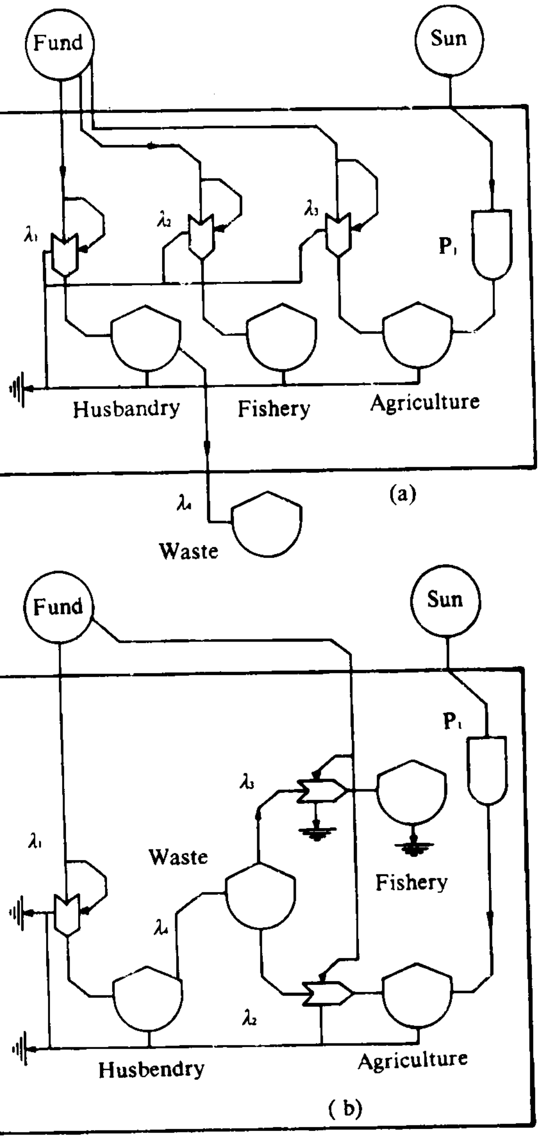

Fig. 2. (a) The model of mono management with waste draining in an ecosystem; (b) The model of compound management with waste using in an ecosystem

In planning an ecosystems engineering, quantitative analysis is the basis of decision-making, and the maximum benefit $E_0(t)_{\max}$ is the goal for regulating the interrelation of components and distribution of investment. There are two ways used to express the economic benefit: the maximum growth quantity N_i' in agricultural production and the maximum productivity $\frac{du_i}{dt}\Big|_{\max}$ in forestry, fishery and animal husbandry production, both can be obtained from the functional extreme values of energy models with respect to investment $E_i(t)$, that is

$$\frac{\partial N_i'[f_i, E_i(t)]}{\partial E_i(t)} = 0 \quad \text{or} \quad \frac{\partial F_i[f_i}{\partial E_i} \tag{3}$$

If the total fund $E_I(t)$ is limited, its reasonable arrangement may result in a maximum benefit of the ecosystem. Define

$$E_I(t) = \sum_{1}^{n} E_{Ii}(t) \tag{4}$$

the maximum benefit can be derived from the simultaneous equation (3) and (4). In the case of limited fund, we have a problem of conditional maximum

$$\left.\begin{aligned} &\frac{\partial\{N_i(f_i, E_i) + \omega E_I(t)\}}{\partial E_i(t)} = 0 \\ &E_I(t) = \sum_{i}^{n} E_i(t) \end{aligned}\right\} \tag{5}$$

or

$$\left.\begin{aligned} &\frac{\partial\{F_i[f_i, E_i(t)] + \omega E_I(t)\}}{\partial E_i(t)} = 0 \\ &E_I(t) = \sum_{i}^{n} E_i(t) \end{aligned}\right\} \tag{5'}$$

where ω is a Lagrange Multiplier, formula (5) and (5)' can theoretically explain the reasonable distribution of energy resource or fund. The increment rate of energy value can be expressed as

$$\eta_i = \frac{N_i}{\int E_i(t)dt} \quad \text{or} \quad \eta_i = \frac{\int E_{Oi}(t)dt}{\int E_{Ii}(t)dt} \tag{6}$$

To apply the energy model to the practice of ecosystems engineering, it is necessary to convert various forms of biomass into energy and transform any human interference related to the ecosystems engineering into equivalents in unit of energy known as "energynization" (variable energynization). For example, in agriculture, forestry, fishery and animal husbandry of an agroforestry ecosystem, the life activity of the biological components and their biomass can be described as energy equation, in which the product value is increased through processing treatment of workers (before the product for sale, the energy is regarded as investment, $E_i(t)<0$; after product sold or its use value being realized, $E_i(t)>0$, $E_i(t)$ is regarded as benefit).

In an agroforest ecosystem, agriculture, forestry, animal husbandry and fishery can be regarded as four ecological entities or subsystems, which form a complete system of biological production. To bring the processing function $P_i(t)$ into equation i means that subsystem i provides processing with energy. Function $P(t)$ indicates the total energy rise value brought by processing, thus we have

$$\frac{du_i}{dt} = F_i[f_i, E_i(t)] - P_i(t)$$
$$P(t) = \sum_{1}^{n} [\xi_i P_i(t) - E_{iP}(t)] \tag{7}$$

where ξ is the rate of energy rise value, and $E_{ip}(t)$ indicates the expense of processing. To use the energy model to describe an ecosystem, 1, 2, 3, 4 are to stand for agriculture, forestry, animal husbandry and fishery respectively, the dynamic energy state of agriculture can be expressed then as follows

$$\begin{aligned}\frac{du_1}{dt} = &(-A_1u_1^2 + B_1u_1) + (C_{12} - D_{12}u_1)u_2 \\ &+ (C_{13} - D_{13}u_1)u_3 + (C_{14} - D_{14}u_1)u_4 \\ &- \varphi_1 + E_1(t) - P_1(t)\end{aligned} \tag{8}$$

Formula (8) can be abbreviated as

$$\frac{du_1}{dt} = I_{10} + I_{12} + I_{13} + I_{14} - \varphi_1 + E_1(t) - P_1(t) \tag{8'}$$

where I_{10} is the energy flux that the agricultural system exchanges with outside of the ecosystem, such as sunlight, fertilizer and waste; I_{12} is the energy flux that agriculture exchanges with forestry such as their rotted leaves and branches; I_{13} is the flux that agriculture exchanges with animal husbandry. Here feeds and animal discharges are obvious examples; I_{14} is that with fishery, such as feeds; as mentioned before; φ_1 is the energy consumption of agricultural subsystem, $E_1(t)$ is the economic benefit and investment including management cost for agricultural production, $P_1(t)$ is the energy needed for processing materials. Other formulas of forestry, fishery and animal husbendry can be inferred from this model in analysis. The model of agroforestry can be further simplified into a so-called "trinity" model, *i. e.* the biological production (agriculture, forestry, animal husbandry and fishery) combined with processing and marketing activities to form a whole ecosystem (Fig. 3) in a broad sense (Hsiung et al. 1995).

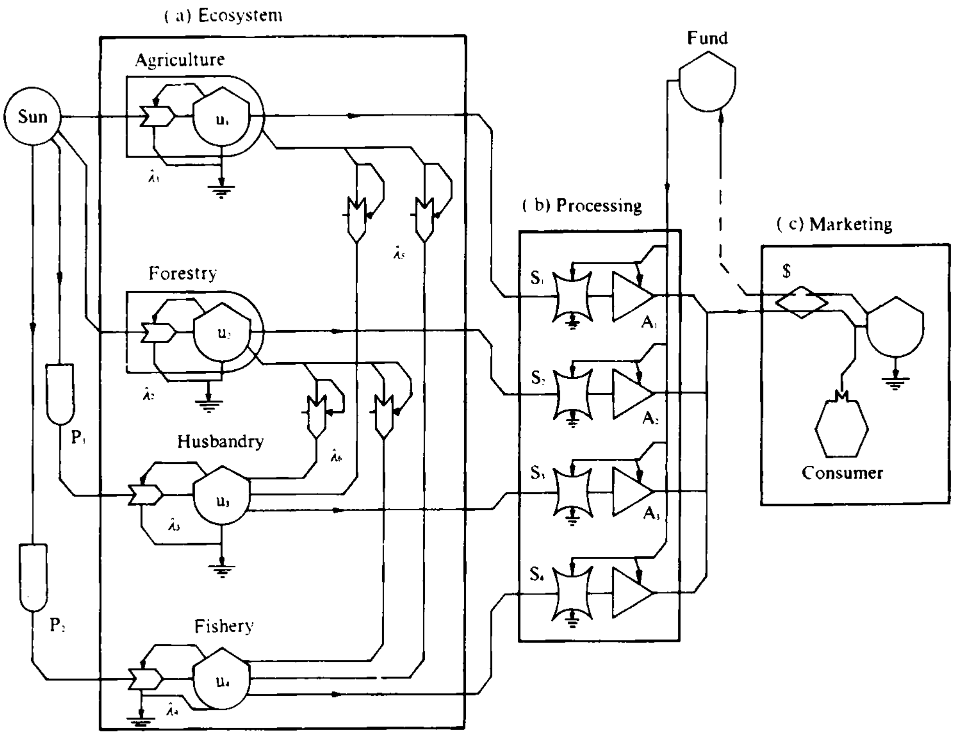

Fig. 3. Sketch map of an agroforestry management ecosystem

All the above description is an example in which a mathematical model is established to analyzes an agroforestry ecosystem, one may simulate it to establish other kind of models of ecosystems engineering in order to calculate investment and benefit, and predict development tendency and regulating situation. From the mathematical analysis of the ecosystem model, we found that the state of energy production may appear chaotic in the ecosystem engineering under some condition. This always happens when energy increases too fast or unbalanced coordination occurs. The mechanism is quite complex. But without the dynamic analysis, one would usually regard the chaotic phenomena as random one.

Conclusive Remarks

It is very common to use energy as a state variable to describe life activities, but we attempt to use energy dynamics to analyze an ecosystem. We visualize that an ecosystem is a functional system of energy flow operated by the life activities of its biological components and can be logically analyzed or illustrated in terms of energy dynamics. Consequently an energy model can be used as an engineering tool for designing, establishing, coordinating and managing any ecosystem in accordance with its expected goals. However, this is just tentative work, further studies are needed.

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